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CO Excitation in Four IR Luminous Galaxies

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The correlation between the CO and far infrared luminosities of spiral galaxies is well established.¹⁻³ The luminosity ratio, $L_{\text{FIR}}/L_{\text{CO}}$, in IR luminous active galaxies is, however, systematically five to ten times higher than in ordinary spirals and molecular clouds in our Galaxy.⁴ Furthermore, the masses of molecular hydrogen in luminous galaxies are large, $M(\text{H}_2) \approx 10^{10} M_{\odot}$, which indicates the observed luminosity ratios are due to an excess of infrared output, rather than a deficiency of molecular gas. These large amounts of molecular gas may fuel luminous galaxies through either star formation or nuclear activity. This interpretation rests on applying the $M(\text{H}_2)/L_{\text{CO}}$ ratio calibrated in our Galaxy to galaxies with strikingly different luminosity ratios. But are the physical conditions of the molecular gas different in galaxies with different luminosity ratios? And, if so, does the proportionality between CO and H₂ also vary among galaxies?

To investigate these questions, we observed CO(2→1) and (1→0) emission from four luminous galaxies with the IRAM 30 m telescope. Three of the galaxies, Arp 193, Arp 220, and Mrk 231, have very high $L_{\text{FIR}}/L_{\text{CO}}$ ratios, and while VII Zw 31 has a moderate luminosity ratio it is one of the most gas rich galaxies yet detected, with $L_{\text{CO}} \approx 10^{10} \text{ K km s}^{-1}$. We mapped each galaxy in the (2→1) line and obtained high quality (1→0) spectra of the center positions. In figure 1 we show the spatial extent of the (2→1) emission and the best fit gaussian distributions. For all of the sources, the FWHM sizes of the (2→1) emission are either smaller than the 13'' beam size or at the resolution limit. This confirms previous findings that molecular gas in active galaxies is concentrated in their nuclei.⁵ The CO morphology of these galaxies is quite distinct from equally gas rich galaxies with low luminosity ratios, such as NGC 1530 and NGC 3147, which we have also mapped, where the CO emission is extended on a scale of 10 kpc. These morphological differences are real, since the 30 m telescope would easily resolve the such extended emission at Arp 220's distance.

The spectra of both lines at the central positions are shown in figure 2. From these spectra we computed the intensity ratios, $I(2-1)/I(1-0)$, listed in the table, correcting for the different beam sizes with both a point source model that provides lower limits to the true ratios and the measured (2→1) source sizes. The ratios are low, less than 0.9 for the three sources with high $L_{\text{FIR}}/L_{\text{CO}}$ ratios. Casoli *et al.*⁶ previously noted a low ratio in Arp 220, but this was fortuitous since their data lack adequate velocity coverage in the (2→1) line and they failed to account for the difference between the beam sizes at the two wavelengths. Although the intensity ratio is a function of the molecular hydrogen density and the gas kinetic temperature, it depends primarily on the density for $I(2-1)/I(1-0) \leq 0.9$, since these low ratios result from subthermal excitation of optically thick gas. Using our observed ratios as constraints, we find for Arp 220 and Arp 193, with measured ratios of 0.6, the local densities⁷ of the emitting gas are in the range $150 \leq n(\text{H}_2) \leq 500 \text{ cm}^{-3}$ for gas kinetic temperatures between 20 and 60 K. For a kinetic temperature $T_k = 25 \text{ K}$ the intrinsic (1→0) brightness temperature excitation $T_b = 8 \text{ K}$ corresponds to an excitation temperature of only $T_{\text{ex}} = 10.5 \text{ K}$, clearly subthermal. Here we note Maloney and Black⁸ dismissed the possibility of subthermal excitation in their calculation of intensity ratios. For a low kinetic

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Quantity	Units	Arp 193	Arp 220	Mrk 231	VII Zw 31
cz	km s^{-1}	7000	5400	12650	16250
D_L	Mpc	94	72	170	220
$I_{\text{CO}}(1-0)$	$\text{K}_{\text{mb}} \text{ km s}^{-1}$	41	109	22	19
$L_{\text{CO}}(1-0)$	$10^9 \text{ K}_{\text{mb}} \text{ km s}^{-1} \text{ pc}^2$	3.1	4.9	5.5	7.8
$I_{\text{CO}}(2-1)$	$\text{K}_{\text{mb}} \text{ km s}^{-1}$	62	155	44	44
FWHM (2-1)	arcsec	14	15	16	18
Source size (2-1)	arcsec	5.2	7.5	9.3	12.4
$I(2-1)/I(1-0)$, if point source		0.55	0.52	0.73	0.85
$I(2-1)/I(1-0)$, with measured (2-1) size		0.61	0.62	0.93	1.22
$M(\text{H}_2)$	$10^{10} M_\odot$	1.3	2.1	2.4	3.1

Gas kinetic temperature, local H_2 density, and intrinsic (1-0) brightness temperature:

$T_k = 10 \text{ K}$: $n(\text{H}_2)$	cm^{-3}	300-1000	300-1000
	$T_b(1-0)$	K	6	6	...
$T_k = 25 \text{ K}$: $n(\text{H}_2)$	cm^{-3}	180-500	180-500	500-1300	...
	$T_b(1-0)$	K	8	8	16
$T_k = 40 \text{ K}$: $n(\text{H}_2)$	cm^{-3}	140-400	140-400	400-800	3000
	$T_b(1-0)$	K	9	9	19
					30

Beam sizes: $(1 \rightarrow 0) = 21.5''$, $(2 \rightarrow 1) = 13''$; $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and $q_0 = 0.5$.

temperature of 10 K, the density could be as large as 1000 cm^{-3} . We find higher ratios for Mrk 231 and VII Zw 31, but suspect telescope pointing difficulties may have exaggerated the measured source size of the latter. For these two the point source model gives ratios near 0.8, which imply $T_k > 20 \text{ K}$ and densities in the range of $500-2000 \text{ cm}^{-3}$.

We can directly estimate the galaxies' total molecular masses by combining our estimates of H_2 densities and intrinsic line brightness temperatures, $T_b(1-0)$, with the observed CO luminosity. If T_{mb} is the observed brightness temperature of the galaxy and A_b is the beam area, the fraction of the beam filled with N_c clouds radiating at the intrinsic brightness temperature is $T_{\text{mb}}(1-0)/T_b(1-0) = (N_c \pi r^2/A_b)(\Delta v/\Delta V)$, where Δv is the velocity dispersion in an individual cloud of radius r and ΔV is the observed line width of the entire galaxy. If the clouds are near virial equilibrium, the dispersion is fixed by the density and radius, $\Delta v = (4\pi G m(\text{H}_2)/3)^{1/2} r n(\text{H}_2)^{1/2}$, and the sum of the individual cloud masses is

$$M(\text{H}_2) = \left(\frac{4m(\text{H}_2)}{3\pi G} \right)^{1/2} \frac{T_{\text{mb}}(1-0)}{T_b(1-0)} \Delta V A_b n(\text{H}_2)^{1/2}$$

This form of the CO mass-luminosity relation for virialized clouds shows the dependence on the observed CO luminosity, $L_{\text{CO}} = T_{\text{mb}} \Delta V A_b$, and on the quantities constrained by the intensity ratio, T_b and $N(\text{H}_2)$. The mass estimates in the table were computed from the $(1 \rightarrow 0)$ luminosity by these formulae.

We conclude most of the CO emission from these galaxies arises in regions with moderate ambient densities similar to the clouds in the Milky Way molecular ring. The emission is neither from dense ($n(\text{H}_2) = 10^4$ or 10^5 cm^{-3}) hot cloud cores nor from the cold low density gas ($n(\text{H}_2) = 100 \text{ cm}^{-3}$) characteristic of the envelopes of dark clouds.

References: (1) Sanders *et al.* 1986, *Ap. J.*, **305**, L45. (2) Young *et al.* 1986, *Ap. J.*, **304**, 443. (3) Solomon *et al.* 1986, 1987, 1988 *Ap. J.*, **334**, 613. (4) Mooney and Solomon 1988, *Ap. J. (Letters)*, **334**, L51. (5) Scoville *et al.* 1986, *Ap. J. (Letters)*, **311**, L47. (6) Casoli *et al.* 1988, *Astr. Ap.*, **192**, L17. (7) Goldsmith *et al.* 1983, *Ap. J. Suppl.*, **51**, 203. (8) Maloney and Black 1988, *Ap. J.*, **325**, 389.

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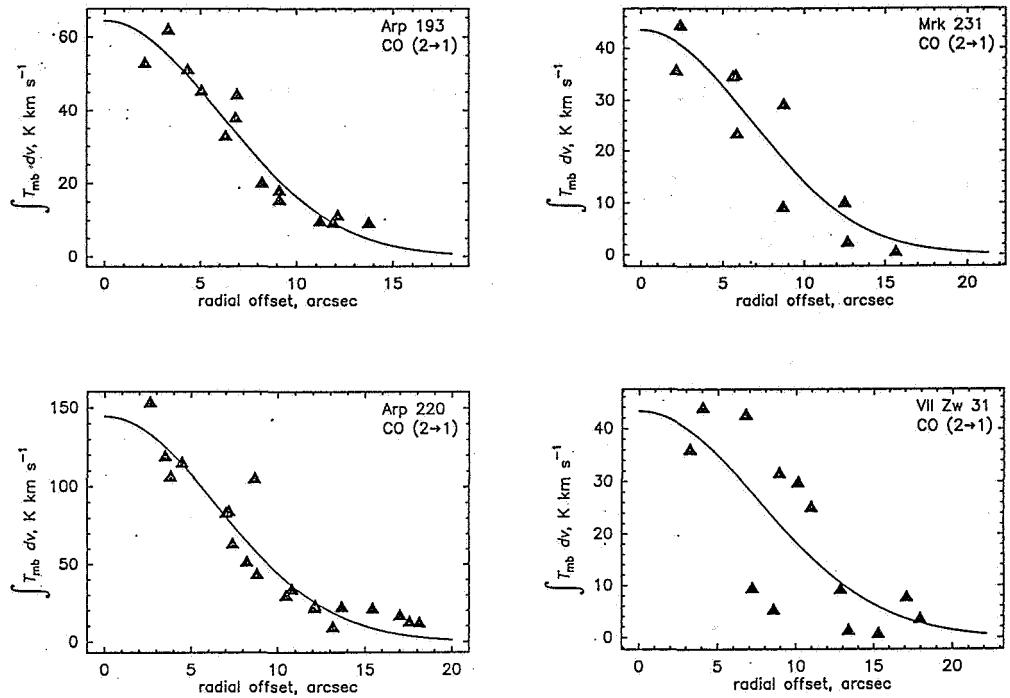


Figure 1. Radial distribution of integrated CO($2 \rightarrow 1$) emission.

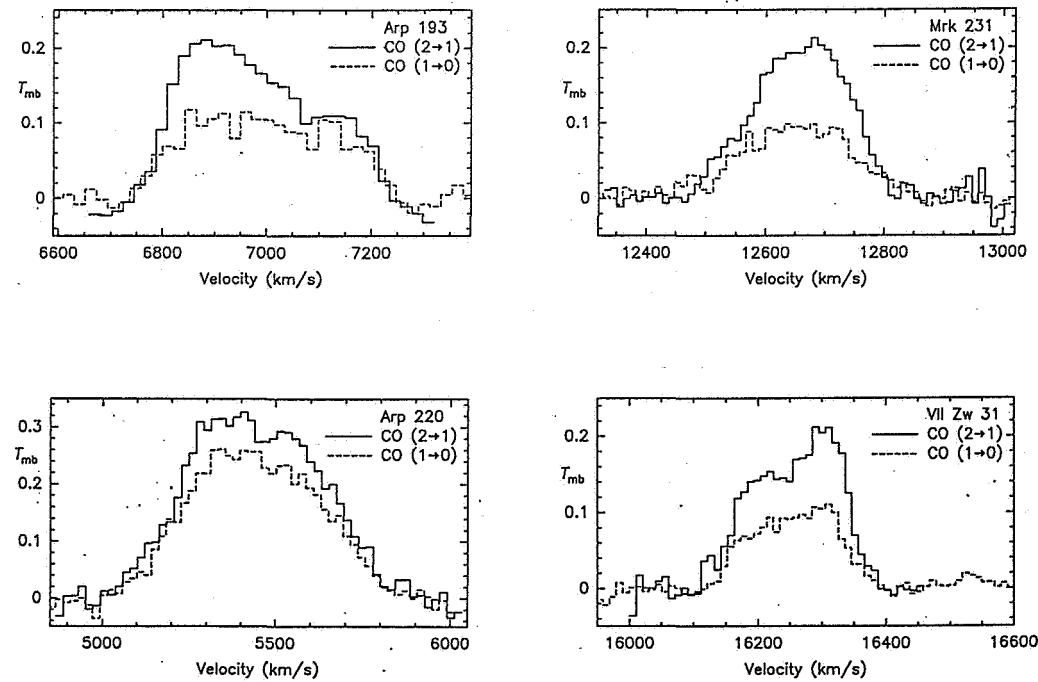


Figure 2. CO($2 \rightarrow 1$) and ($1 \rightarrow 0$) spectra at central positions.